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Hydrodynamic Stability and Magnetic Reconnection in Disks and Stars

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HYDRODYNAMIC STABILITY AND MAGNETIC RECONNECTION IN DISKS AND STARS

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Hydrodynamic Stability

With Dongsu Ryu and Ethan Vishniac, the PI has further explored an $m = 1$ internal-wave instability of accretion disks that was discovered by the PI under a previous NASA Theory Grant, NAGW-2419 ([6], henceforth G93), and has been reexamined since ([7], [8], [9]). In brief, tidal distortions of the disk destabilize internal waves—nearly nearly incompressible disturbances whose wavelength is comparable to the disk thickness or smaller. These waves require either a radial gradient in specific angular momentum, or a vertical gradient in entropy or molecular weight; both gradients should be of a sign that normally makes for stable oscillations, but nevertheless these waves are parametrically destabilized by tides. It had been shown earlier by Vishniac & Diamond that $m = 1$ internal waves may transport angular momentum radially through the disk [10], but a robust mechanism for exciting the waves had been lacking. G93 pointed out that since other processes may also transport angular momentum, the parametric internal-wave instability may be most important in limiting the outer radius of the disk, because tidal excitation of the waves entails a retarding torque on the disk and a transfer of angular momentum to the companion.

The stability analyses of [6] through [9] are local in radius. Paper [1] therefore addresses the following two issues:

(i) The local growth rate was is a strong function of radius because the tidal distortion is strongest at large radii; but the modes excited locally propagate globally, and a valid prescription for the global growth rate was lacking.

(ii) The internal waves are excited in pairs: one wave propagates inward, and the other outward. It has been suggested [7] that the instability is suppressed unless the waves are well reflected at the outer radial boundary, which most likely they are not.

By allowing for artificially rapid radial variations in the tidal terms, Paper [1] demonstrates that the global growth rate is essentially the maximum local growth rate, provided that maximum is attained over a radial interval Δr satisfying $\Delta r > V_g \tau$, where V_g is the radial group velocity, and τ is the local growth time. This condition is rather easily satisfied. Under the same conditions, the radial boundary conditions are irrelevant, unless the range Δr includes a boundary. The resulting picture of the global instability is one in which waves are rapidly excited near the outer edge of the disk and propagate inwards. Since they have negative angular momentum density, the waves carry an outward angular momentum flux.

With Pawan Kumar [2], the PI has applied parametric instabilities to binaries formed by "tidal capture," the process whereby two stars on an unbound relative orbit become bound as tides near periastron excite modes of oscillation in their interiors. Tidal capture probably contributes to the high abundance of low-mass Xray binaries and millisecond pulsars in globular clusters (cf. [11] and references therein). In tidal capture, low-order f and g modes are excited by direct tidal forcing, not parametric instability. Evolution of the binary immediately after capture depends, however, on how the oscillations damp. If they damp slowly compared to the orbital period, energy may return to the orbit and even disrupt the binary [12], although the latter is perhaps unlikely [13]. If the oscillations damp rapidly in the outer parts of the stars, the envelopes will swell up and the stars may merge at a subsequent periastron [14]. In fact, conventional dissipative mechanisms (radiative diffusion, convective turbulent viscosity) operate on timescales $\sim 10^4$ yrs.

The f- and g-mode amplitudes resulting from tidal capture are very large. The typical energy per mode is $10^{42} - 10^{45}$ erg $\equiv 10^{42} E_{42}$, whereas solar five-minute oscillations have $\sim 10^{28}$ erg/mode. The dimensionless radial amplitude $\delta R_*/R_* \geq 0.002 E_{42}^{1/2}$. By direct calculation of the 3-mode coupling coefficients, Paper [2] shows that these large amplitudes in the low-order modes cause growth rates $\sim 0.2 E_{42}^{1/2}$ d^{-1} in parametrically resonant high-order g-modes, and that the number of such modes is $\sim 10^{10} E_{42}^{5/4}$. Consequently, most of the energy in the low-order modes will be lost in ~ 50 d, which though long compared to the time near periastron, is usually shorter than the initial orbital period. Furthermore, since g-modes in low-mass stars are confined to the radiative core, the tidal energy is ultimately deposited

in the core, whose binding energy is $\sim 10^{48}$ erg, so that the structure of the star may be very little affected by tidal capture. Globular-cluster stars above 0.5 $M_\odot$ have radiative cores; dissipation in lower-mass stars is expected to be much slower.

One would like to understand the importance of parametric instability in other types of close binaries where the tides are much weaker than in tidal capture. In such cases, the secular dissipation rate depends not only on 3-mode coupling of low-order to high-order g-modes, but also on interactions of high-order modes among themselves. The problem involves an inertial-wave turbulence similar to that studied by oceanographers [15], and it is impossible to be confident of results obtained purely analytically. A student, Michael Blanton, and the PI have undertaken direct 3D numerical simulations in an idealized rectangular geometry. Construction and testing of an appropriate spectral code has recently been completed, and results should be available within the coming year.

Magnetic reconnection

The process of reconnection is of considerable importance to understanding many important astrophysical problems. In rotating accretion disks it provides a natural saturation limit to the Balbus Hawley instability. In order for reconnection to happen in a highly conducting plasma it is first necessary that a very thin current layer develop.

A student, Victoria Dorman, and Kulsrud have been exploring various ways to trigger the formation of this layer. One method which they found was to introduce an increase in cooling rate into the plasma in the neighborhood of the null of a magnetic field. This cooling tends to reduce the pressure and the resulting imbalance of forces makes the plasma contract about the layer to restore equilibrium. This contraction leads to rapid formation of a very thin current layer. As long as cooling in the layer is strong enough to overcome ohmic heating, the thickness of the layer continues to decrease, and the rate of reconnection continues to increase. When a balance is reached the rate of reconnection becomes constant. If cooling always dominates ohmic heating, then reconnection of the all the magnetic flux occurs in a finite time. (These results are reported in [3].) It is interesting that the cooling process is quite close to a similar but two-dimensional process for forming the layer in which the plasma is squeezed out of the null region in a direction parallel

to the layer at the Alfven speed. The cooling rate corresponds to the Alfven speed divided by the length of the layer. Again the plasma layer settles down to a thickness such that ohmic heating offsets adiabatic cooling of the plasma by the two-dimensional flow.

In another paper, Dorman shows that a magnetic reconnection layer can also be formed by enhancing the recombination rate, an alternative way to reduce plasma pressure [4]. In each of these cases the question is not only how does the layer form, but also how thin does the layer become before it reaches a steady state? The thinner the layer that is reached the faster the resulting reconnection. (All these results comprise Dorman's Phd dissertation.)

Another student, Dmitri Uzdensky, and Kulsrud have attacked the general problem of the rate of magnetic reconnection [5]. They have shown that any two dimensional reconnection problem can actually be broken into two parts, a global one and a local one. They have shown that on the global scale the plasma is in a state of static equilibrium everywhere except in the reconnection layer itself and in a narrow separatrix region into which the plasma flows from the reconnection region. The equilibrium is uniquely determined once the amount of reconnected is specified. The only unknown is the rate at which the magnetic field reconnects. Thus, with time, the plasma proceeds through a sequence of states of predetermined equilibrium at a rate determined by the rate of reconnection. The global conditions then provide a complete set of boundary conditions for the local problem of the physics in the reconnection layer.

Using the upstream boundary conditions, the incoming velocity normalized to the reconnection rate, and the magnetic field, it appears possible to solve for the physics in the reconnection layer for any rate of reconnection from that of Sweet Parker up to that of Petschek. However, when one also demands that this solution must match to the downstream conditions involving the flow of plasma leaving reconnection into the separatrix region it appears that only one rate of reconnection is possible. The chief purpose of this research is to understand a magnetic reconnection experiment being carried out at the plasma physics laboratory, the MRX. However, the test of the agreement of the analysis with the experiment will also be a test of how well we understand the reconnection phenomena in a real laboratory situation. In addition, it is hoped that detailed experimental probing of the layer itself will aid understanding of the general process of magnetic reconnection.

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